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RESEARCH MEMORANDUM

COMPONENT PERFORMANCE INVESTIGATION OF

J71 EXPERIMENTAL TURBINE

IX - EFFECT OF FIRST-STATOR ADJUSTMENT; INTERNAL FLOW CONDITIONS OF J71-97 TURBINE WITH 87-PERCENT-DESIGN STATOR AREA

By Harold J. Schum, Donald A. Petrash, and Elmer H. Davison

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WASHINGTON
April 30, 1957

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RESEARCH MEMORANDUM

COMPONENT PERFORMANCE INVESTIGATION OF J71 EXPERIMENTAL TURBINE

IX - EFFECT OF FIRST-STATOR ADJUSTMENT; INTERNAL FLOW CONDITIONS OF J71-97 TURBINE WITH 87-PERCENT-DESIGN STATOR AREA

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SUMMARY

An experimental radial-survey investigation of the J71-97 three-stage turbine equipped with a first stator having a throat area 87 percent of the design value was conducted at one turbine operating point. The first-, second-, and third-stage mass-averaged efficiencies were 0.897, 0.843, and 0.755, respectively. The corresponding over-all turbine efficiency was 0.856.

The results of the 87-percent turbine survey investigation, when compared with corresponding results obtained from previous investigations conducted on the same turbine but having first-stator areas 70 and 97 percent of design, indicate that the interstage flow conditions varied considerably, but the over-all turbine efficiency for all three turbine configurations remained constant at about 0.86.

INTRODUCTION

The effect of first-stator throat area changes on the component performance of an experimental J71 three-stage turbine is currently being investigated at the NACA Lewis laboratory. The over-all performance characteristics of this turbine, when equipped with first stators whose throat areas were nominally 70-, 87-, 97-, and 132-percent of the design area, are reported in references 1, 2, 3, and 4, respectively. Over this wide range of first-stator area adjustment, the maximum obtained over-all turbine efficiency was high, varying by only 2 points, between 0.87 and 0.89.

A compressor-turbine match-point analysis was conducted in reference 4, based on an arbitrary mode of engine operation during which the compressor was maintained at constant equivalent design conditions. The 70- and the 97-percent turbines were then operated at or near this match point, and the interstage flow conditions were investigated in an effort to determine the changes in flow effected by these first-stator area changes. These results are presented in references 5 and 6. The object of the subject report is to present the results of a similar survey investigation conducted on the 87-percent turbine when operated at its turbine match point. The results of this investigation are compared with those previously obtained with the 70- and the 97-percent turbines. For all three turbine configurations, however, it should be stated that the results are not considered quantitative; but, because the methods used were similar for all three investigations, they can be interpreted as indicating trends of comparative performance. 4300

SYMBOLS

The following symbols are used in this report:

c	blade chord, ft
p	pressure, lb/sq ft
s	blade spacing, ft
T	temperature, $^{\circ}$R
β	relative flow angle (measured from axial direction), deg
η	efficiency based on measured total temperatures and pressures
σ	solidity, ratio of actual blade chord to blade spacing, c/s
$\overline{\omega}$	loss coefficient, $(p_i'' - p_o'')/(p_i'' - p_o)$

Subscripts:

i	inlet
o	outlet
0,1,2,3 4,5,6,7	measuring stations (see fig. 2)

Superscripts:

'	stagnation or total state
"	relative stagnation or total state

APPARATUS AND INSTRUMENTATION

The first-stage stator of the 97-percent turbine was replaced with one having a throat area 87 percent of the design value for this investigation. This area change was obtained by resetting the stagger angle of the design blade profiles. The test installation used for the subject turbine survey investigation (fig. 1) was the same as that used in the 70-percent and the 97-percent survey investigations. The over-all test setup is described in detail in reference 7, but, for all three survey investigations, the turbine was modified to incorporate third-stage rotor shrouding as described in reference 6.

A schematic diagram of the turbine showing the axial and circumferential location of the instruments is given in figure 2. Radial measurements of total pressure, total temperature, and flow angle were made using combination probes mounted in remotely controlled movable actuators. With a combination probe (fig. 3(a)), data were obtained at the turbine inlet (station 1, fig. 2) and at the outlet of each succeeding stator blade row at a single circumferential position. At the outlet of each rotor blade row, these data were obtained from two actuators located at different circumferential positions. In addition to the total-pressure, total-temperature, and angle measurements, radial measurements of static pressure were made by replacing the combination probes with static-pressure wedges of the type shown in figure 3(b).

METHODS AND PROCEDURE

Turbine matching characteristics were determined for the subject 87-percent turbine in reference 2, based on an assumed engine mode of operation during which the compressor is maintained at constant equivalent design conditions. The survey investigation of this turbine was conducted at the equivalent match speed of 3088 rpm and an equivalent work output of 34.17 Btu per pound, which closely approximated the turbine match requirements of reference 2. The turbine-inlet total pressure and temperature were nominally 35 inches of mercury absolute and 700° R, respectively.

At the outlet of the first-stage stator (station 2, fig. 2), the radial static-pressure variation was obtained by assuming a linear variation between the average of the values measured by the wall static taps on the inner and outer shrouds rather than by using values obtained from the static-pressure wedge. This procedure was necessitated by the fact that the first-stator-outlet absolute Mach number was considerably greater than that for which the static-pressure wedge produces reliable results. The radial variation of static pressure at all other measuring stations was obtained from the static-pressure wedges. Where duplicate sets of measurements were obtained behind each rotor, the measurements were numerically averaged at their corresponding radial positions. All parameters used in this report to describe the internal flow conditions through the turbine were calculated by the procedures described in reference 6.

RESULTS AND DISCUSSION

The internal flow conditions are presented herein in terms of stage work parameter $\Delta T'/T'$ and stage efficiency η as functions of annular flow area. Over-all turbine performance characteristics, based on turbine-inlet and turbine-outlet measurements, are included. In addition, the radial variations of Mach number and flow angle as observed behind each blade row are presented. The corresponding results of the survey investigations of the 70-percent turbine (ref. 5) and the 97-percent turbine (ref. 6) are shown herein in order that the stagewise radial variations of all these parameters with changes in first-stator throat area can be noted. For ease in the ensuing discussion, each of these parameters is discussed individually.

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Work Parameter

Figure 4(a) presents the radial variation of the stage work parameter $\Delta T'/T'$ with percent of rotor-outlet annular area for the 87-percent turbine. Included in this figure is the over-all turbine work parameter, based on turbine-inlet and -outlet temperature measurements. Indicated on the ordinate of each curve is the mass-averaged value of work parameter. Also shown are similar results from the 70-percent turbine (ref. 5) and the 97-percent turbine (ref. 6) investigations.

For any particular stage, no comparison of the magnitudes of the work-parameter curves (fig. 4(a)) for the three turbine investigations can be realistically formulated, because the turbine match-point equivalent work at which all three survey investigations were conducted was different (see fig. 9, ref. 2). However, the mass-averaged values of the work parameter for each stage represent a percentage of the over-all turbine work output. A comparison of this stage work division for the three turbine survey investigations is summarized in the following table:

Stage	Stage work division, percent		
	70-Percent turbine (ref. 5)	87-Percent turbine	97-Percent turbine (ref. 6)
First	49.8	47.0	42.9
Second	20.8	29.7	32.3
Third	29.4	23.3	24.8

As the first-stator throat area was reduced, the percentage work output of the first stage of the turbine was increased at the turbine operating match point. Conversely, the percentage work output of the second stage was decreased. Not much change in the third-stage percentage work output occurred until the first-stator area was reduced to 70 percent of design. For this turbine configuration the third stage was highly loaded because
4300 the turbine was operated very near limiting loading.

Spanwise, the trends of the work-parameter curves (fig. 4(a)) for the 87-percent turbine are, in general, similar to those observed for the 97-percent turbine. Regions of low work parameter persist near both the hub and tip for all blade rows, and this is naturally reflected in the same trend for the over-all work-parameter curve.

Efficiency

The spanwise variation of stage and over-all efficiencies for the 87-percent turbine is shown in figure 4(b), along with the corresponding curves for the 70- and 97-percent turbines. Mass-averaged values for the 87-percent turbine are indicated on the ordinate of each curve. In general, the radial efficiency trends for all the curves are similar, with regions of lower efficiency near the hub and tip. It will be noted, however, that, although there is quite a variation of individual stage efficiency characteristics for the three turbine configurations, not much change can be observed in the over-all turbine efficiency.

To better observe the stage and over-all turbine-efficiency variations, the mass-averaged values for all three turbine configurations are listed in the following table:

Stage	Stage and over-all turbine efficiencies		
	70-Percent turbine (ref. 5)	87-Percent turbine	97-Percent turbine (ref. 6)
First	0.900	0.897	0.891
Second	.759	.843	.849
Third	.828	.755	.784
Over-all	0.865	0.856	0.858

It is apparent from this table that the mass-averaged first-stage efficiency is relatively constant for all three turbine configurations, even though the throat area of the first stator was varied from 70 to 97 percent of the design area. This area change corresponds to a total change in the stagger angle of the design blade profile of about $8\frac{1}{2}^{\circ}$ (see fig. 7, ref. 2). There are considerable changes in the second- and third-stage efficiencies with first-stator throat area, however.

It is interesting to note that the trends of the efficiency data with first-stator throat area follow the same patterns as those observed for the stage work division; that is, as the stage work distribution either increased or decreased with first-stator area, the stage efficiency values varied similarly. Although both parameters varied considerably for the three turbine configurations, the mass-averaged turbine over-all efficiency remained almost constant at 0.86.

Interstage Flow Velocities and Angles

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The radial variations of the absolute and relative Mach numbers and flow angles entering and leaving each rotor blade row are presented in figure 5 for the subject turbine and the two reference turbines. Also included are the radial variations of the design values as obtained from the design velocity diagrams presented in reference 8. In general, the absolute and relative flow angles at the inlet and outlet of the first-stage rotor (fig. 5(a)) are of the same order of magnitude as those obtained in the 97-percent turbine. The relative flow angle at the rotor inlet indicates that an angle of incidence (defined as the deviation from the design flow angle) on the order of 6° to 8° is present on the first-stage rotor. The absolute rotor-outlet flow angle indicates that the second-stage stator is operating with an incidence angle of about 8° to 12° over most of the blade span.

The absolute and relative Mach numbers at the outlet of the first stator (inlet to the first rotor) for the 87-percent turbine are considerably greater than the design values. As would be expected, these Mach numbers are higher than those obtained from the 97-percent turbine survey, and lower than those observed in the 70-percent turbine investigation. The radial variations and magnitudes of the Mach numbers at the outlet of the first-stage rotor are similar to those observed in both reference turbine investigations.

Figure 5(b) shows that the absolute and relative Mach numbers at the inlet and outlet of the second-stage rotor for the 87-percent turbine have the same general radial characteristics as the two reference turbines. However, the 87-percent turbine Mach number curves closely approach the design Mach number distribution, particularly when compared with the corresponding curves for the 70-percent turbine. In general, the same comments pertain to the flow-angle distributions shown in figure 5(b). That the Mach number and flow-angle data for the 70-percent turbine are farthest removed from the design distribution may be a contributing factor to the low second-stage efficiency for this turbine, as noted in the aforementioned efficiency tabulation.

The relative flow angle at the rotor inlet for the second stage of the 87-percent turbine (fig. 5(b)) indicates that a small amount of incidence is present in the hub and tip regions of the blade span. The absolute outlet flow angle on this curve indicates that incidence angles on the order of 4° to 16° exist on the third-stage stator at the turbine operating match point.

Figure 5(c) indicates that the radial variations of Mach numbers and flow angles at the third-stage-rotor inlet for all three turbine configurations are similar. The levels of the Mach number curves for the 87-percent turbine are reasonably similar to those observed for the 97-
4300 percent turbine (ref. 6), with the subject turbine more closely approaching the design values. The relative inlet flow angle indicates that the third-stage rotor of the 87-percent turbine is operating with an angle of incidence on the order of 4° to 8° over most of the blade span. The flow angles at the turbine outlet are near the design values except for a limited region of underturning near the blade tip.

Loss Function

The variation of the stage loss function $(\bar{\omega} \cos \beta)/\sigma$ with percent rotor-outlet annular area is presented in figure 6 for all three stages of the 87-percent turbine, the 70-percent turbine (ref. 5), and the 97-percent turbine (ref. 6). The stage loss function $\bar{\omega}$ is the relative total-pressure drop across the rotor divided by the difference between the relative inlet total pressure and the static pressure at the rotor outlet and, for any particular stage, assumes there is no total-pressure loss in the stator. Figure 6 indicates that the level of the loss-function parameter curve for the first stage of the 87-percent turbine is lower than the corresponding curves for the two reference turbines. In general, the level of the loss function for the second and third stages for the subject turbine lies between those observed for the two reference turbines. The trends of the curves for each stage of each turbine configuration exhibit the same general characteristics. Regions of highest loss parameter persist in the hub and tip portions of each rotor blade span.

SUMMARY OF RESULTS

A cold-air radial-survey investigation of the J71 experimental three-stage turbine with a first stator having a throat area 87 percent of design was conducted at a predetermined turbine operating match point. The results were compared with corresponding results previously obtained with the same turbine having first-stator throat areas of 70 and 97 percent of design. The following results were obtained:

1. The mass-averaged values of efficiency for the first, second, and third stages of the 87-percent turbine were 0.897, 0.843, and 0.755, respectively.

2. Although the first-stator throat area was changed considerably, the efficiency of the first stage remained relatively constant. The efficiency of the second and third stages varied considerably for each turbine configuration. However, the over-all turbine efficiency for all three configurations remained constant at about 0.86.

3. Mach numbers at the outlet of the first-stage stator of the 87-percent turbine were considerably higher than design. In general, both the flow angle and Mach number distributions behind succeeding blade rows were nearer design than for either the 70- or 97-percent turbine configurations. 4300

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, February 18, 1957

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Figure 1. - Installation of J71-87 experimental three-stage turbine in full-scale turbine-component test facility.

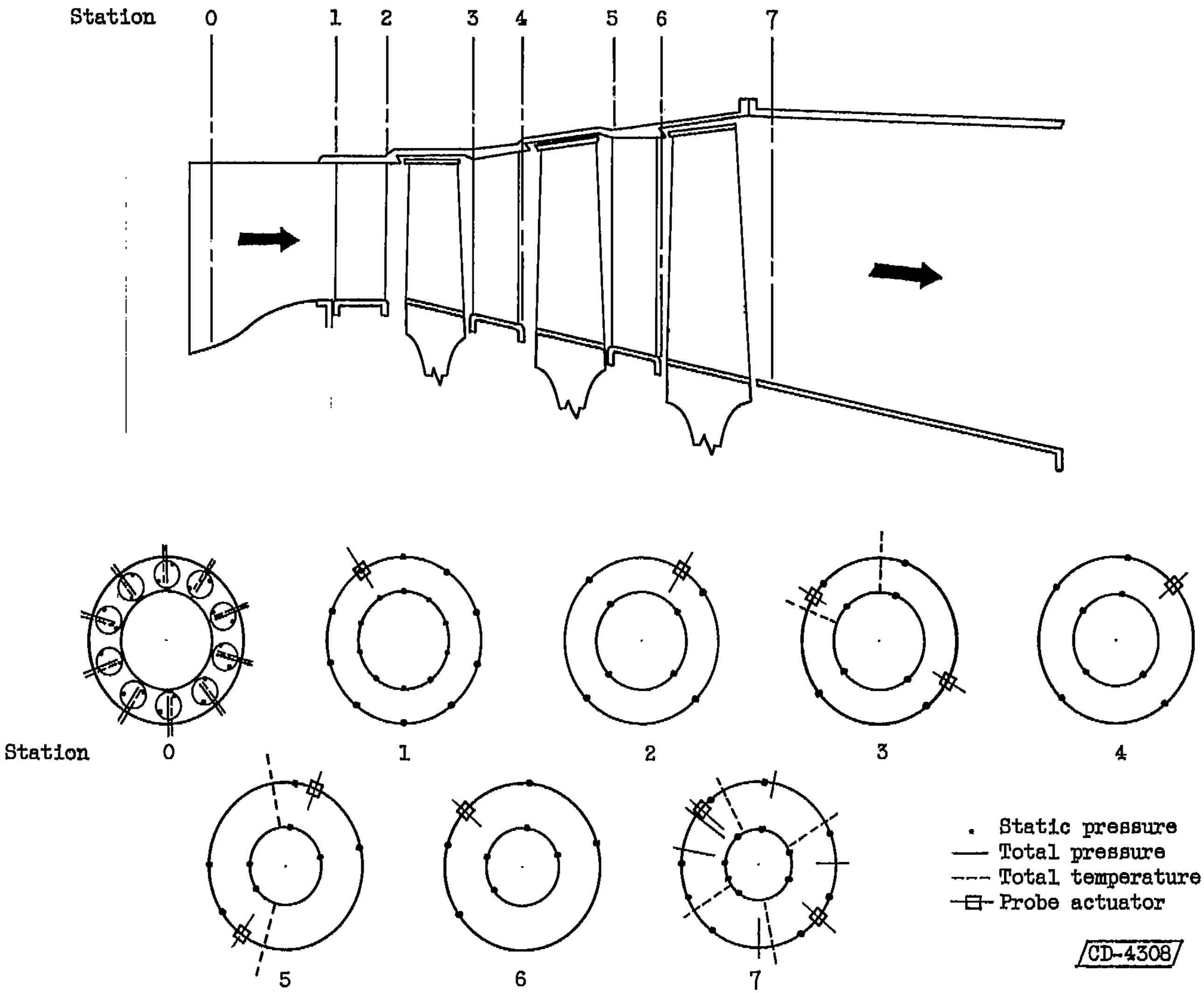
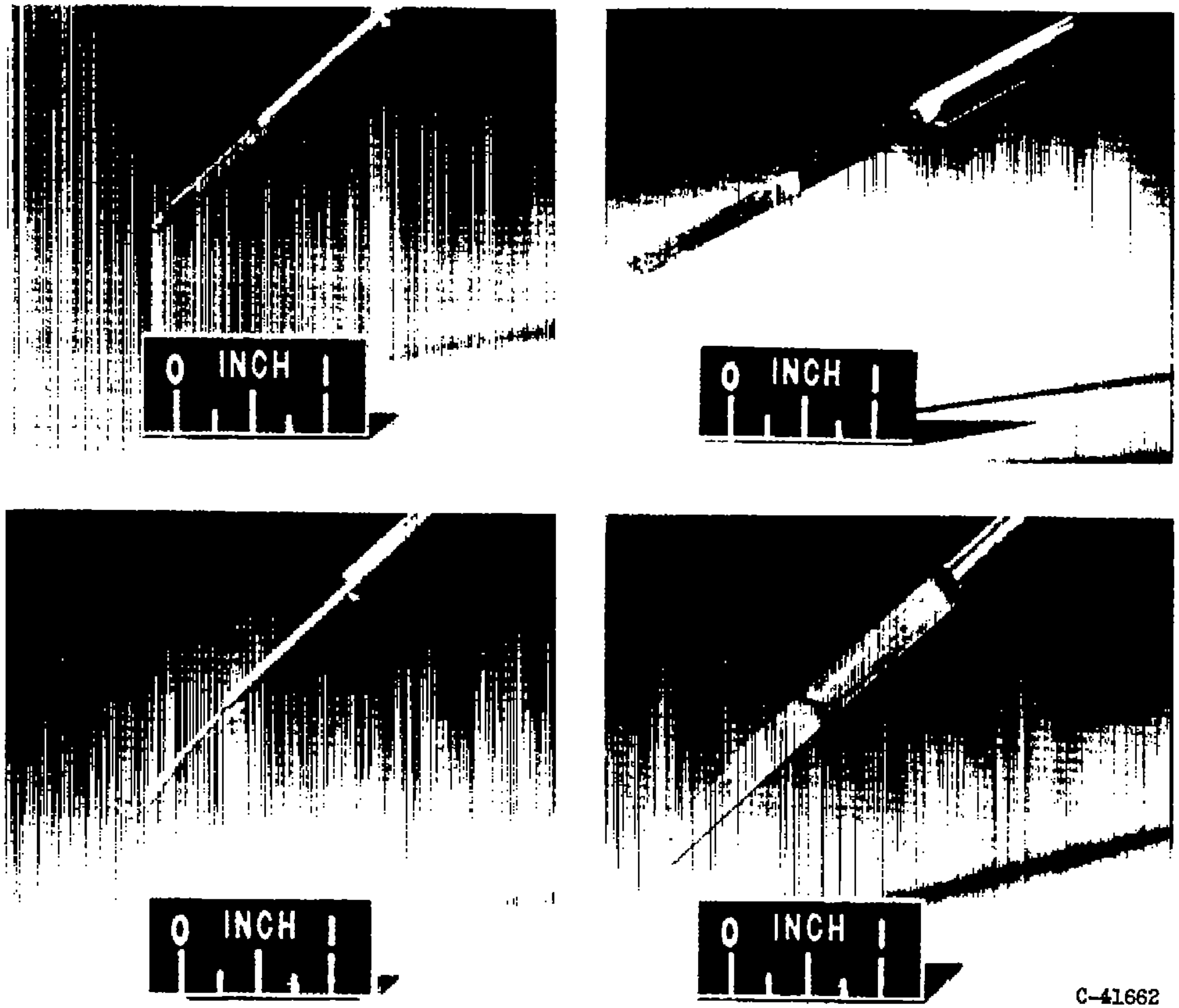


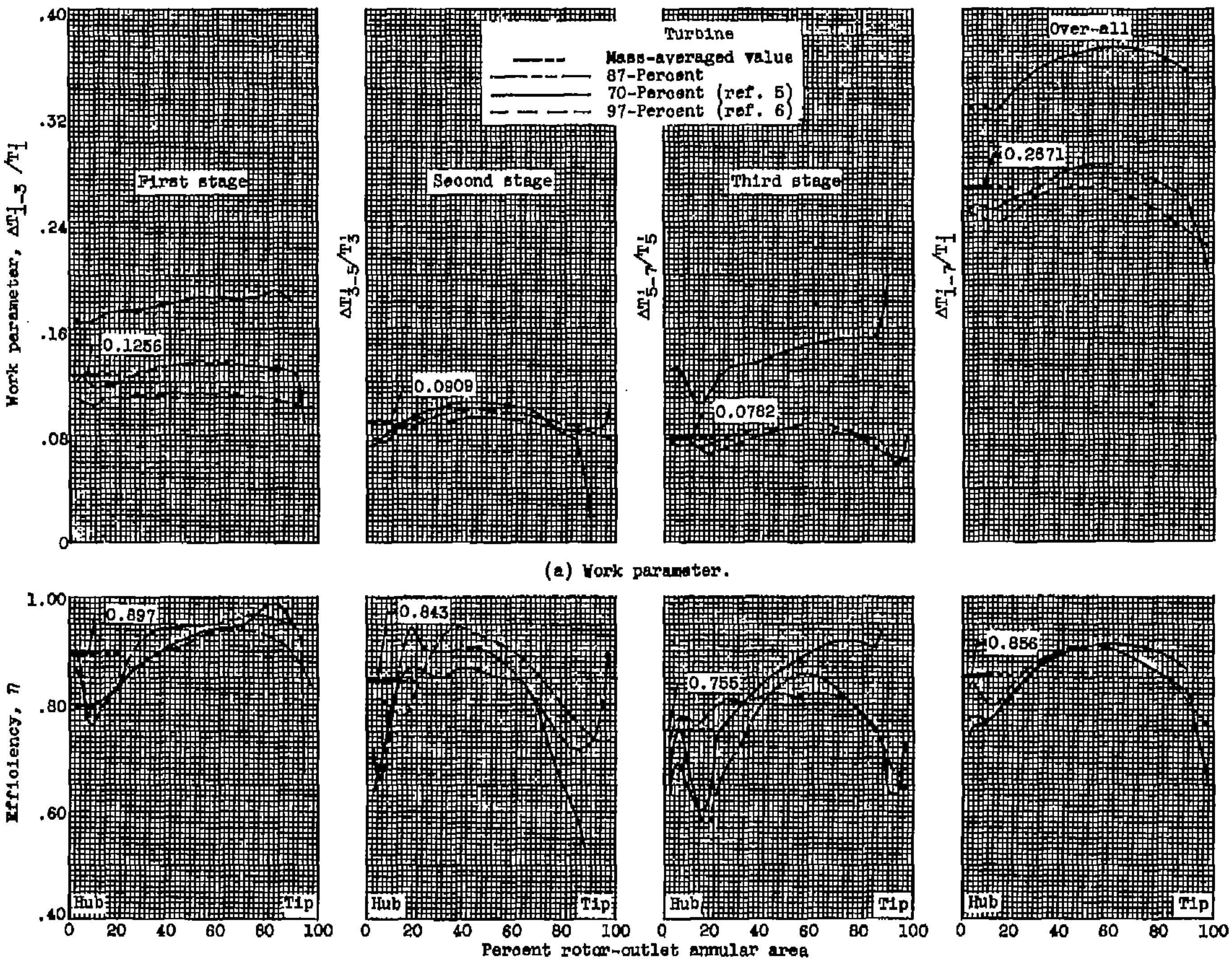
Figure 2. - Schematic diagram of J71-87 turbine showing instrumentation.



(a) Total-pressure, total-temperature, and angle probe.

(b) Static-pressure wedge.

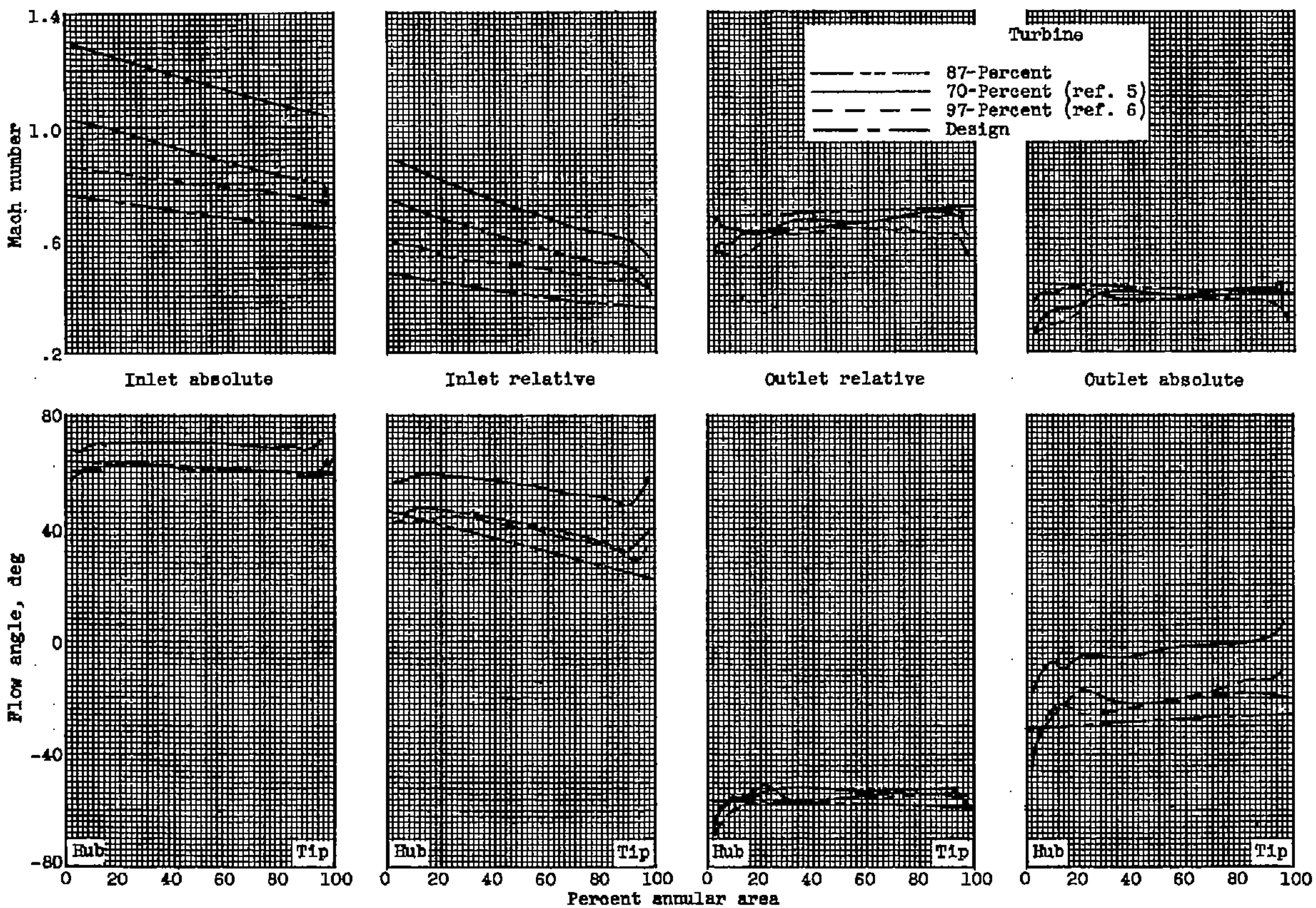
Figure 3. - Typical static-pressure wedge and probe for measuring total pressure, total temperature, and angle.



(a) Work parameter.

(b) Efficiency.

Figure 4. - Variation of stage and over-all work and efficiency with annular area at rotor outlets.



(a) First rotor.

Figure 5. - Variation of absolute and relative Mach number and flow angle at rotor inlet and outlet with annular area.

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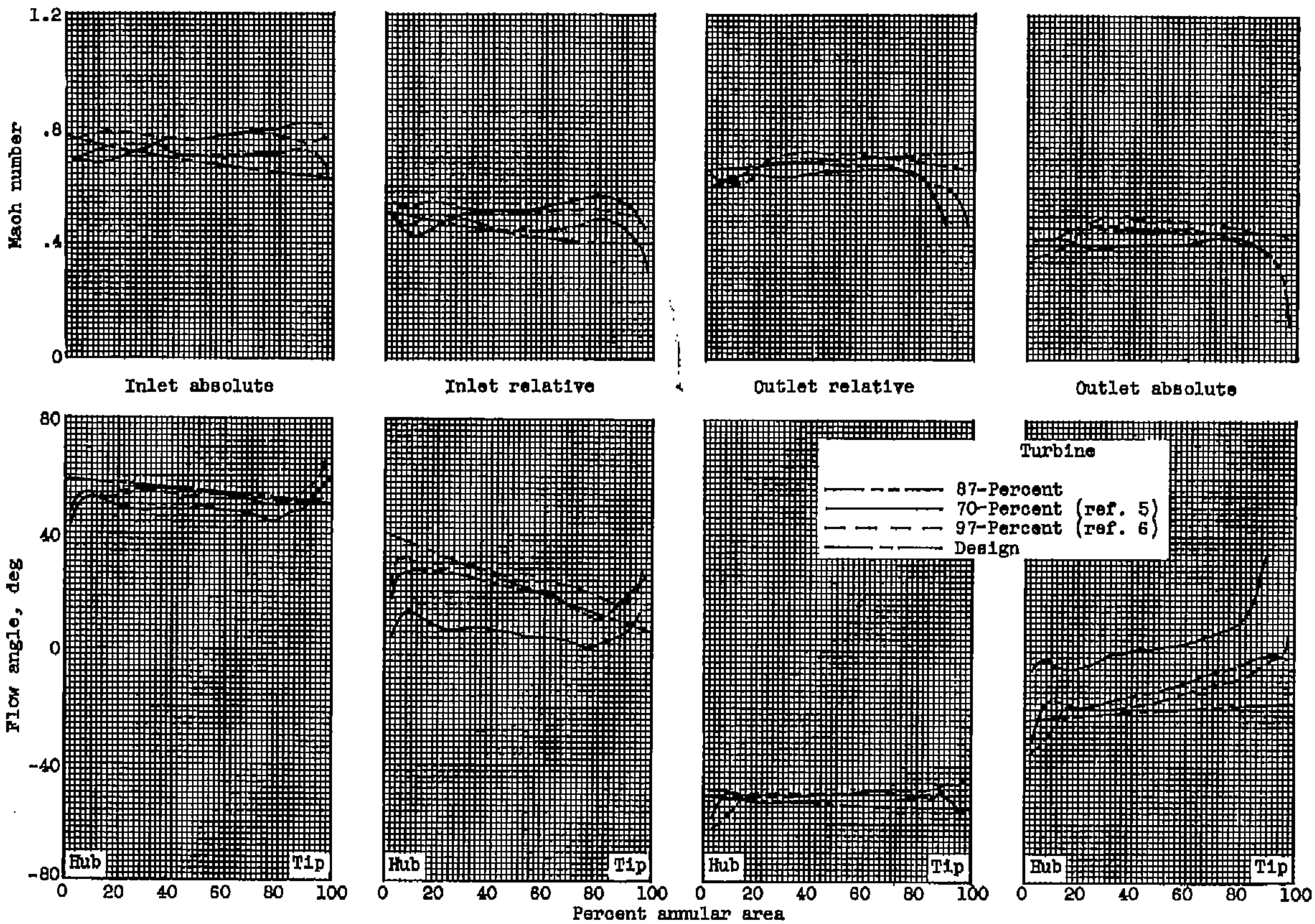
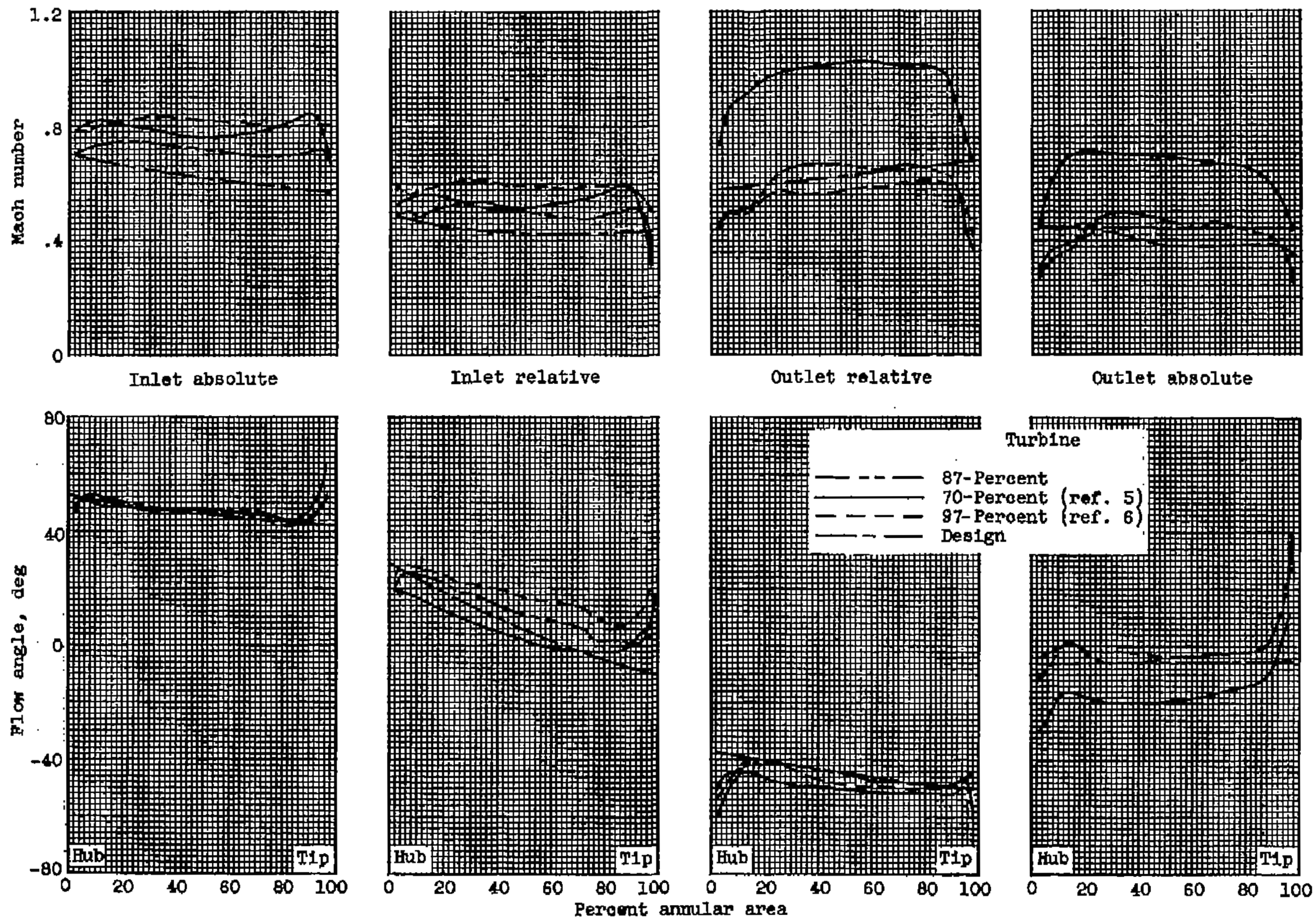


(b) Second rotor.

Figure 5. - Continued. Variation of absolute and relative Mach number and flow angle at rotor inlet and outlet with annular area.



(c) Third rotor.

Figure 5. - Concluded. Variation of absolute and relative Mach number and flow angle at rotor inlet and outlet with annular area.

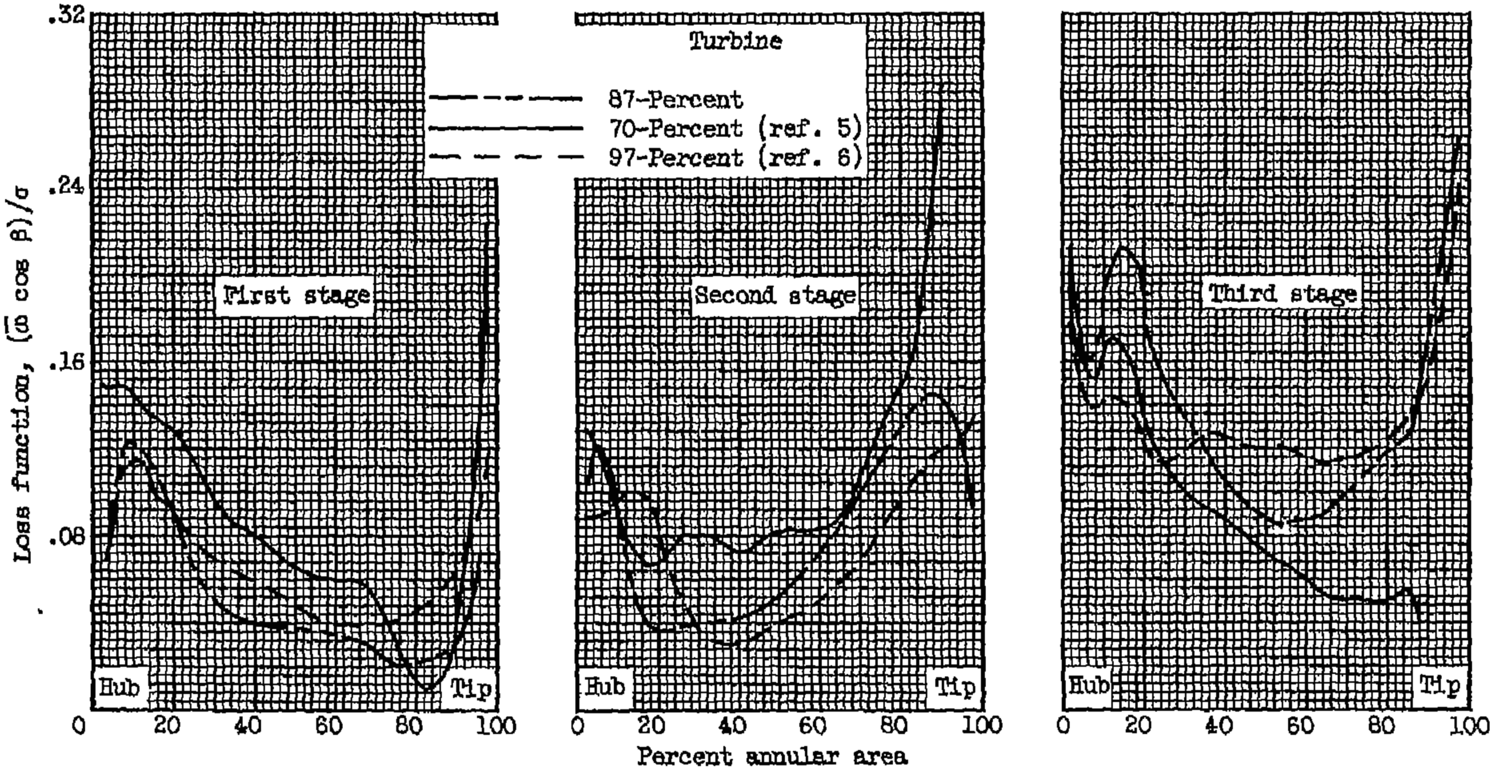


Figure 6. - Variation of loss function with annular flow area.

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